Reduction of Noise by Principal Component Analysis in On Line Frequency Response Monitoring of Power Transformers

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***Abstract*—A method for the analysis of signals of On Line Frequency Response Monitoring, using Principal Components, is described in this article. The method is shown to be useful when the signal of the test has noise which could distort the original data and lead to misinterpretation of the results by giving a negative statement even when the transformer is still in good condition. It is shown that with Principal Components the noise could be reduced and the analysis could be performed closer to the actual state of the equipment. For the evaluation of signals, a method based on the Standard Deviation was used.**

***Index Terms*—On Line Frequency Response Monitoring, Principal Component Analysis, Transformers**

I. Introduction

POWER transformers are very important elements of Power Systems. Their function of transforming voltage from one level to another has made it possible to reach long distances from the sources of electricity to the final customers, decreasing the effects of losses and low voltage regulation in the system. Thus, the energy of a city, state or even a country could depend on the availability of these devices.

Therefore, it is important to have power transformers in good condition, and implement maintenance policies so that their faults can be avoided or predicted. The maintenance activities are usually performed by means of tests such as turns ratio, isolation resistance, power factor, frequency response analysis (FRA), etc.

FRA is a relatively new technique, the first standard related to this test was developed in China and was published in 2005 [1], and after that, IEEE presented its own standard in 2012 [2]. That is why it is usually not possible to find this test in recent specifications of utilities or in general standards related to power transformers [3]. The FRA test is based in the fact that any internal movement of the elements of the equipment will change the behavior of the magnetic and electric field which will be reflected in the equivalent inductances and capacitances of the transformer. Thus, the resonance and antiresonance frequencies will change and could be taken as reference to evaluate the internal condition of the power transformer.[7]

For the FRA test, a signal of voltage between 2 and 20 V is applied to the terminals of the transformer; the frequency of this signal varies from 10 Hz to 2 MHz [4]; then a voltage signal is measured in other terminal of the transformer, and the transfer function between the input and the output signal is obtained. In the determination of the transfer function, both magnitude and angle are compared [5].

The main advantages of FRA test are the possibility to find failures of the transformer which are not possible with other tests, and that there is no need to dismantle the transformer. The disadvantages are that, in order to perform the test, the transformer must be de-energized, and there is not a common way to interpret the results of the test [5].

The FRA test could be used for two purposes: for modeling and for diagnosis. The necessity to have a model to know the behavior of the transformer before high frequency transients has made it important to use FRA signals to model the machine [6]. On the other hand, diagnosis of the transformer is a maintenance activity, which has to be done whenever it is suspected that the internal parts of the equipment have changed, for example during transportation, after earthquakes or if a short circuit current of considerable value has been circulating through the windings for a relative long time.

The two most popular ways to interpret FRA signals are by an expert observation and by quantitative comparison of signals. The former is very subjective and in case the results are bad for the equipment, the criteria belongs to only one person who is considered the expert; however, it is the most common in the industry and is the method usually shown in FRA testers manuals [7]. The comparison of signals depends on the data available; if the FRA test has been done in the factory, immediately after the transformer has been built, this result could be used as a finger print for future tests; on the other hand, if the factory data is not available, the test could be compared with the results of similar units; finally, if both type of tests do not exist, the test could be compared with the other phases of the same transformer, in case it is a three phase unit [4]. One of the recommended method of comparison [10] is by the Standard Deviation, which must be less than 1 to consider that the equipment does not have internal problems.

FRA test, as it is done off line, need the transformer to be de-energized. This makes its application performed between long periods of time or even only for acceptance purposes. For that reason, nowadays trend is to get an on line FRA test, however there are some issues that need to be solved first: the connections for an on line test are difficult, the output signals could be influenced by the power system voltage and there could be noise that distorts the signal [8].

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II. Principal Component Analysis Background

PCA is a technique where a set off data is modified so that the main correlations are more evident than in the original data. This is achieved by the change of the coordinate axes to new ones which will be orthogonal and with the tendency to be in the direction where the most important correlation is located [9].

The principal components can be obtained by two ways, according to the matrix being used in the process: the covariance or the correlation matrix. The former, whose process is explained below, is used in the method developed in this paper.

First, subtract the mean to the data (1), so that the final vectors are located around the zero vector, i.e. the mean of the new values is zero. If the data, because of the units of measure, has significant differences in the variance, the $\bar{X}$ matrix could be standardized by dividing it by its variance, but this is not the case of the problem analyzed in this study.

$$\bar{X}_{ij} = X_i - \frac{1}{n}X_j \tag{1}$$

$\bar{X}$ is the matrix with the centered data. n is the number of data for each individual or for each case, and X is the matrix with the original data.

Second, calculate the covariance matrix of $\bar{X}$ (2).

$$\bar{X}_{cov} = cov(\bar{X}) \tag{2}$$

Third, calculate the eigenvectors and the eigenvalues of the covariance matrix. They constitute the principal components and their variance (3).

$$\bar{X}_{eig} = eig(\bar{X}_{cov}) \tag{3}$$

Fourth, choose the components to be taken into account. This is done by examining the eigenvalues calculated before. According to the desired certainty (4), numerically expressed as the explained variability (EV) [11], a number of eigenvectors will be kept for the final computations.

$$EV = \frac{\sum_{i=1}^{k} \lambda_i}{\sum_{i=1}^{n} \lambda_i} \tag{4}$$

k is the number of eigenvectors to be chosen and λ is the eigenvalue for each eigenvector.

Finally, derive the new data set and the original modified data (5).

$$X_{new,n\times p} = B_{n\times k} \times V^T_{p\times k} \tag{5}$$

X_{new} is the new set of data derived from the chosen eigenvalues, p is the number of cases, B is the projection of the original data on the orthogonal system of coordinates, V^T is the transposed matrix with the eigenvalues, note that only the first k eigenvalues are used.

III. Discussion and Results

As it was stated in the introduction, noise is one of the problems when the FRA test is going to be implemented on line. That noise could be eliminated by PCA; since noise is not an important part of a signal, when the most valuable components are chosen, a great part of the noise could be eliminated, and thus a cleaner signal would be obtained. The method presented in this section has been widely applied in the analysis of resonances in mechanical and civil engineering [12].

In order to get the FRA signals for the analysis, simulations of the transformer under variation of frequency from 10 to $2 \times 10^6 Hz$ have been performed and the transfer functions in form of diagrams have been obtained. The model of the transformer has been taken from [6]. In Fig. 1 the signals for the original data are shown.

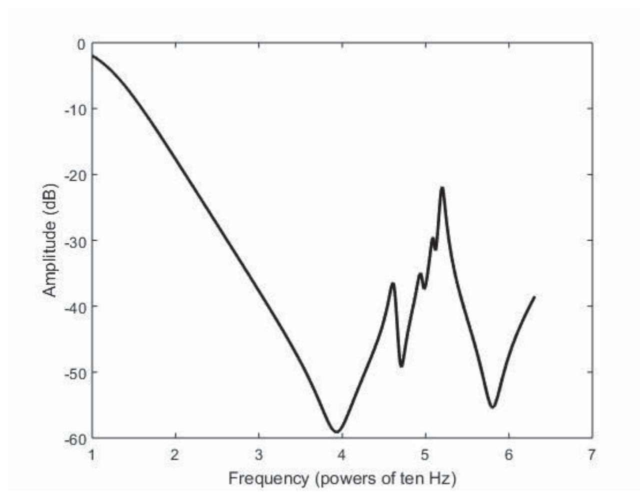

Fig. 1. FRA signals for an undamaged transformer

A. Transformer in Good Condition

In [10] it is said that the transformer is in bad condition if the standard deviation defined by (6) is greater than 1. This criteria will be taken in the following discussion. The matrix with the data of the tests when the transformer is in good condition will be called X; this will be formed by columns that represent each of the simulated cases.

$$SD_{x,y} = \sqrt{\frac{\sum_{i=1}^{N}(X_i - Y_i)^2}{N-1}} \tag{6}$$

N is the number of data for each case, and X and Y are the data for each of the curves to be compared.

A transformer whose capacitance has varied in 8% for low frequencies has been simulated. The FRA signal is shown in Fig. 2. Note the slight variation in the first resonance frequency. For this transformer, the standard deviation is 0.366, which means that the transformer, usually could be considered to be in good condition.

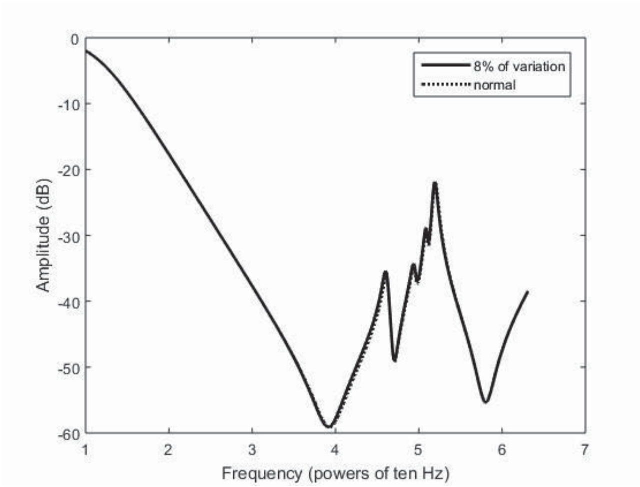

Fig. 2. FRA signals for a Transformer with an 8% variation in the low frequency capacitance value. The curve for an undamaged transformer is also included so that the slight variation around 10^4 Hz is appreciated.

If the FRA signal for this transformer has a noise of about 5%, the standard deviation is 1.7250. This means that, because of the noise, the transformer could be considered in bad condition, although it is not. See Fig. 3.

The data of the last test, included noise will be augmented to X in its first column, this will create a new matrix that will be called X_{noise}. PCA is applied to X_{noise} and the vectors and coefficientes are obtained. The values for this PCA are shown in Table I.

Almost the whole FRA signal is explained by the first component. If this component is taken to recover the data of the test, which means, reducing the whole analysis to only one dimension, the standard deviation is 0.1190. The FRA signal, once filtered with PCA, indicates that the transformer

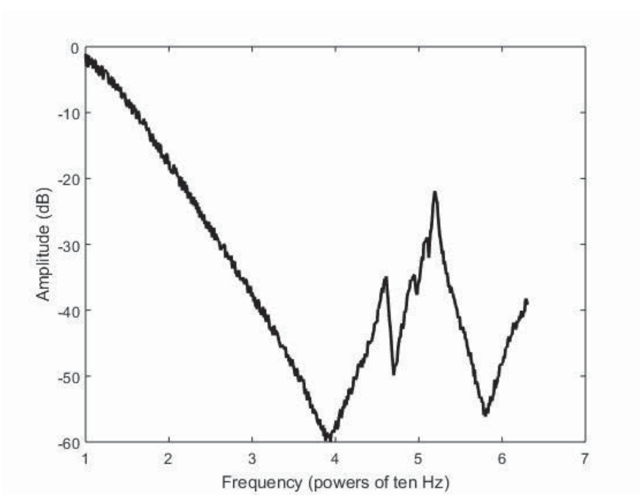

Fig. 3. FRA signals for a Transformer with an 8% variation in the low frequency capacitance value with noise

TABLE I
PCA ANALYSIS FOR THE TRANSFORMER WITH AN 8% OF VARIATION IN CAPACITANCE

Variable	Value
Acumulated Sum of Eigenvalues	5370.5
First Eigenvalue	5370.3
Second Eigenvalue	0.1618

is in good condition as it was when there was not noise. In Fig. 4 both FRA signals, FRA test of the transformer and the filtered signal are shown together. Note that the noise has been vanished.

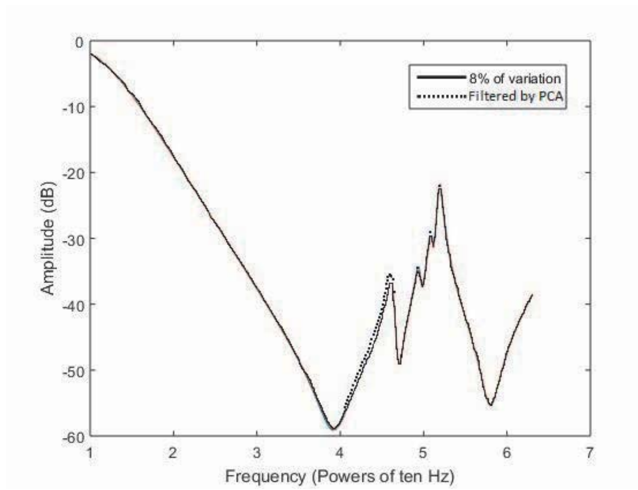

Fig. 4. FRA signals of the last test and the signal filtered by PCA

B. Transformer in Bad Condition

If a transformer is in bad condition, the method must show this condition and the filtering should not change the diagnostic of the device. If not, it could result in a useless on line FRA test. To see if this is true, a transformer with a 20% change in the low frequency capacitance will be analyzed. The standard deviation in this case is 3.4387 which clearly indicates that the transformer has a problem. When noise has been included, the standard deviation is raised to 3.6346.

Fig. 5 shows the FRA results for this transformer compared with the original signals. Note the displacement of the signal, which for an expert observer will be an indication of the internal damage of the equipment.

The procedure is the same as before, the 20% signal is included in the matrix X and the PCA is applied. The new standard deviation is 1.7697. This means that the transformer is still considered in bad condition, although because of the principal components, the signal is closer to the base FRA signal.

IV. CONCLUSIONS

A new method to analyze FRA signals has been proposed. It is based on Principal Component Analysis. The method

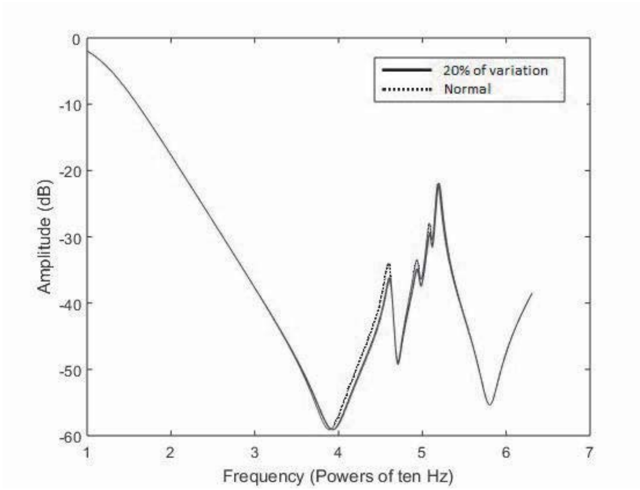

Fig. 5. Comparison of FRA signals for a 20% change in the low frequency capacitance

is useful when noise could distort the diagnostics and by it, a misinterpretation of the signal is avoided. This method could have a strong application when the on line FRA test is implemented.

When using Principal Components to analyze FRA signals, the signal to be compared tends to be like the ones of the base data. This could cause trouble when the new data is obtained, since it will be more alike the fingerprint of the transformer. One must be careful by checking if this behavior does not influence in the FRA interpretation.

The method should be studied further when the ways to interpret FRA signals are more common for the whole standards. In the meantime, the PCA application for FRA has been validated only by comparison through Standard Deviation.

Further analysis must be done related with the limits of the method proposed in this article. It should be established what problems could arise if cases with a Standard Deviation close to one are going to be analyzed. It is apparent that there could be possible mistakes during the analysis with PCA. A research where fuzzy logic is applied in these cases could be developed in the future.

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